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Wireless Networks: Implications for Aircraft Loads Monitoring

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ABSTRACT

A variety of new wireless technologies offer some advantages when used for direct strain monitoring of rotating components, particularly for rotary wing aircraft. This technical note investigates some of these technologies, including one developed in house by Air Vehicles Division. The use of wireless technology is advantageous as it avoids the use of slip rings and other current methods for monitoring strain where the component to be investigated rotates relative to the rest of the vehicle. Investigation of these same technologies for use when retrofitted to fixed wing aircraft or in non-rotating components is also presented. In this situation the advantage offered by these devices is the simplicity, convenience and speed with which they can be applied to usage and loads assessment. It is concluded that DSTO should adopt wireless sensors for an array of load monitoring uses and actively research in leading areas such as power harvesting.

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Executive Summary

Strain and load monitoring of aircraft structures is a well established method for determining component lifetimes. This is typically conducted under two activity groups; Operational Load Monitoring (OLM) or Health and Usage Monitoring (HUM). OLM is a program of limited duration seeking to gain a snapshot of loads associated with operational use and is not used to directly life an aircraft. HUM is an ongoing activity that tracks and determines the life of aircraft and components. HUM can have a wide range of implementations, from fairly simple systems for fleet usage tracking up to detailed strain or loads monitoring on individual aircraft. The simpler and less accurate methods require greater margins of safety and result in less cost effective utilisation of life.

Both OLM and HUM can be conducted on fixed and rotary wing aircraft. However, rotary wing applications are limited by the ability to transmit data and power across the fuselage to rotating component interfaces and older airframes are not able to benefit from newer monitoring technologies without expensive retrofit actions. This paper sets out to determine whether advances in wireless monitoring technologies can bridge both of these issues and provide benefits to the ADF.

Currently there are operational restrictions on wireless devices within Defence. These restrictions are considered with respect to this advancing technology and possible solutions to limitations discovered are explored in the first section of this document. A brief investigation into the state of the art of wireless sensor networks is then conducted before assessing commercially available systems. Following this the commercial systems are considered in light of the data, power and environmental requirements of commercial and military applications. Predictions are made into possible developments in this field and their impact on strain and loads monitoring for aircraft.

It is concluded that DSTO should utilise more commercial wireless measuring technology, where the system requirements allow. In addition, DSTO should not attempt to enter the commercial development and miniaturisation of the technical components. Instead it should invest time and effort into research of newer areas of the technology, such as power harvesting, where ingenuity could lead to novel solutions that have the potential to revolutionise the field and benefit the ADF.

Contents

1. Introduction

Existing methods of load monitoring are expensive and time consuming to install. When a dynamic or rotating component is to be monitored, this is further complicated by the need to use slip rings or some other device to transfer data between the moving and stationary components. New wireless technologies offer the possibility of directly monitoring the loads in stationary, dynamic and rotating components cheaply and easily.

This report discusses some of the shortcomings of existing methodologies of strain monitoring, with a focus on operational loads monitoring in fixed wing aircraft and measuring of loads in rotating components of rotary wing platforms.

The current defence policy on wireless networks is focussed on the use of wireless devices in an office environment. This policy is discussed in terms of the requirements for flight tests and operational loads monitoring.

Growth in the area of wireless devices has also lead to a growth in both published works and web based companies exploiting these areas. The published works focus on academic pursuits and research in the area, while the web based systems are focused on companies with innovative devices to sell. Included in this section is a description of an innovative strain recording device created within the Air Vehicles Division (AVD), as part of the AVD Ideas Program.

This report details attempts to contact local suppliers of wireless devices. These suppliers were given a typical specification for both flight testing and operational loads monitoring. They were then asked to respond to the specification with their devices and capabilities.

The final part of this report discusses some predictions of future growth in wireless monitoring. Included in this section is the impact of some of the innovative products, such as self powering modules, coming online.

2. Existing Methods for Strain Monitoring

Broadly speaking there are three main areas of interest for strain monitoring. The first is flight test. This is highly accurate, intrusive and limits the types of operations an airframe can perform. It is typically only applied to a single aircraft within a fleet and only for a short period of time for specific flight tests.

The second area is Operational Loads Monitoring (OLM). This type of strain monitoring is applied across a larger number of aircraft; it does not limit operational use of the aircraft. The monitoring is performed over a longer period of time on in service aircraft.

Finally, there is Health and Usage Monitoring Systems (HUMS). These are applied across entire fleets, for long periods of time (ideally the airframe life). They do not limit the operational use of the aircraft.

Only the first two of these are within the scope of this report, although many of the conclusions can be applied to HUMS aspects.

2.1 Flight Test

The current state of the art for strain and acceleration monitoring involves sensors wired back to a central ruggedised computer. Typically a strain gauge or accelerometer is fastened to an area of interest and a wire threaded back to a central data rack. The data rack contains an amplifier and signal conditioner for each sensor. The output from the signal conditioning is then fed into a ruggedised computer for storage on the computers hard drive.

This style of measurement technology is still used widely within DSTO. Typical sensor numbers for a flight trial are around 200 strain gauges and 50 accelerometers. Each of these sensors will require sufficient wire to run back to the central computer. On a Black Hawk that may average 20 meters per channel. On a fixed wing aircraft a reasonable estimate of average wire length per sensor may be half the wingspan plus 50% to account for deviation of wiring around obstructions.

In terms of cost, the sensors themselves are relatively cheap. Installation and material costs of the wiring start at around $40 per installed meter of cabling (250 x 20 x 40 = $200,000). The computer is approximately $5000 and the amplifier and signal conditioners are around $100 each (total $25000).

A complete strain survey of a Black Hawk, involving 250 sensors will cost approximately $230,000. Much of this cost is installation of the wiring looms. If these looms are required to be attached to airframe components then additional cost may be involved in clearing any engineering modifications to the airframe. These were the orders of magnitude for cost, of a full strain survey completed on the S-70A-9 Black Hawk in 2001. Although this trial did use wireless transmission of the data back to a base station, it also stored the strain data on-board for later download.

2.2 Operational Loads Monitoring

The setup noted above for Flight Test requirements, would be similar to an operational loads monitoring program for a fixed wing or rotary wing platform. However, in an operational loads monitoring program, the monitored aircraft doesn't stay close to a base station so wireless transmission of data to an off-board destination is not possible. Wireless sensors can still be used but the data need to be transmitted to on-board receivers for later download, or stored in the sensor and wirelessly transmitted to off-board sensors.

As a comparison for costs of wireless systems the Portable Strain Gauge, discussed in section 5.1, is a 3 channel device with an expected cost of less than $150 per channel and installation costs of around $100 per device (3 channels). For a similar strain survey of

250 channels this would be less than $50,000. Although the Portable Strain Gauge is not a wireless device (data is stored in on board flash RAM devices), this capability could still be expanded to for around $100 per device (a total of less than $10,000). A toughened portable computer ($5000) would then be required for storage of the data.

2.3 A Note about Load Measurement on Rotating Components

Loads monitored on rotating components, such as main and tail rotor components on a rotary wing aircraft, require a slightly more complex method of data collection. The current system for collecting those data is with the use of a device called a slip ring. This is a standard method of collecting data where the subject component rotates relative to the place where the data storage module is mounted, typically inside the cabin.

A slip ring consists of a series of rotating and stationary contacts with a sliding brush connecting them. The strain gauge, accelerometer or other sensor signal is passed through the contacts which maintain electrical connection continuously.

In the case of helicopters, slip rings are fitted in the main and tail rotor and occasionally in drive shafts. These are flight critical components and any modifications in these areas are checked thoroughly.

Early versions of this system had low signal-to-noise ratios, but more modern slip rings generally offer acceptable levels of noise at quite high data acquisition rates. The use of wireless sensors may not offer an improvement over slip rings in terms of signal-to-noise ratio, but they will offer significant benefits in other areas, such as cost.

In order to maintain low noise levels in the slip ring, regular maintenance is required. Slip rings tend to be high precision and thus expensive pieces of equipment, and finally they are often quite bulky and require extensive engineering checks as they require modifications in critical areas of machinery.

3. Defence Policy on Wireless Connectivity

As wireless connectivity has found its way into more devices, the ability to transfer data without the presence of cables has expanded. Wireless protocols like Bluetooth, GPRS[1], WiFi or 802.11b/g are used to send data between communication devices like mobile phones, laptops and PDAs[2]. This style of connectivity can equally be used to send information between remote sensors to a central data storage unit, or information can be stored on the sensor and downloaded to a portable device.

Use of these devices within the defence security environment has two major drawbacks. The first of these is the contents of the message, which may contain classified or mission sensitive

[1] General Packet Radio Service.

[2] Personal Digital Assistants.

data, may be intercepted by a third party. Secondly the emission of wireless signals may indicate to enemy forces, the presence of a covert unit.

Despite these concerns, DSTO and defence policy is not well developed and is necessarily strict. Reference [1] at section 14 indicates:

> *Wireless Networks are computer systems that use radio or infrared technology, rather than cable to connect and communicate.*
>
> *Wireless networking shall not be used for any Defence systems without using an approved DSD product for encryption or a permission to operate has been granted. In all other cases, the wireless capability shall be disabled e.g. Notebook computers with built-in "Bluetooth" technology.*

That is the extent of the discussion of wireless networking. It is clear from this that the focus of this policy is on the interception of restricted transmissions, rather than the detection of a covert asset.

Despite this there are a number of safe ways to use wireless devices that will prevent both transmission of restricted data and inadvertent betrayal of a covert asset. The first issue to asses is the classification of the risk. For a flight trial where the platform will be exclusively used in a trial then there is little risk from either aspect. This means that the information being transmitted is of little value to a perceived threat and the asset is not being used covertly so it will not matter if electronic emissions are detected. This would be the case, for example, where a strain survey is completed on a platform at ARDU[3] or a training aircraft with no operational value, such as a Kiowa or a PC-9.

For an operational loads monitoring program on an aircraft that may be deployed to an area of operations where hostile forces operate, then the risk is much higher. In this situation the opposing forces may be able to use any detected information to reconstruct mission information, or they may simply use the detection of electromagnetic emissions to give advanced warning of an overflight.

Most situations will not be at either of these extremes, but will invariably require some thought as to the possible risks associated with use of wireless devices.

Having assessed the risk the next step is to formulate a method to protect against that risk. At the extreme of risk it may be decided to disable the system for a particular flight, with the knowledge that this will affect the output of the operational loads monitoring program.

Alternatively, lower power transmitters can be used to ensure that the wireless sensor network information cannot be transmitted past the geographic extremes of the network. Some care is required here. Firstly, depending on the nature of the transmitters, side lobes can be created which would allow detection at larger distances in unexpected directions. Secondly, the power required to transmit information is greater than the power required to

[3] Aircraft Research and Development Unit.

just be detected. The system will need sufficient power to transmit its data with the minimum of errors. At these power levels detection of the emissions will still be able to be made at greater distances even though the information will not be able to be read.

As a final method of defence, the download system may be enabled by the weight-on-wheels switch. This system would allow wireless transmission of the data only when the aircraft is on the ground.

A system has been developed within AVD as part of the AVD Ideas Program [2], which uses the Bluetooth protocol to communicate with devices such as Flight Data Recorders and other maintenance and safety equipment. The device establishes a communication link and then downloads the contents of the equipment. A switch is provided on the maintenance equipment that only allows downloading when the aircraft is on the ground. The enabling switch could be the weight-on-wheels switch, or a switch on the particular maintenance device.

Secure technologies exist for wireless networks at RESTRICTED and SECRET level. The process to accredit a particular trial or operational set-up is to identify products on the Defence Signal Directorate Evaluated Products List and then pursue accreditation through Defence Signals Authority.

As this section has shown, there are a number of problems with introducing wireless devices into the defence system. There is an existing defence policy that limits the use of wireless devices. However, sensible risk assessment procedures, combined with already existing security measures, should not place any unnecessary limitations on the use of wireless sensors for operational loads monitoring.

4. Published Wireless Sensor Network Information

In this section a selection of four, recently published books are reviewed with a view to strain monitoring of components and retrofitting of strain monitoring systems. This selection is by no means exhaustive and further information is easily achieved with a simple search of the DSTO research library catalogue. This section is meant as a guide to the sort of published work available and focuses both on currently available technology and longer range research in the field.

The four books reviewed are;

- Wireless Sensor Networks: An Information Processing Approach, by F. Zhao and L. Guibas [3].
- Wireless Sensor Network, edited by C.S. Raghavendra, K.M. Sivalingam and T. Znati [4].
- Handbook of Sensor Networks: Compact Wireless and Wired Sensing Systems, edited by M. Ilyas and I. Mahgoub [5].
- Sensors, Nanoscience, Biomedical Engineering, and Instruments, edited by R.C. Dorf [6].

4.1 Wireless Sensor Networks: An Information Processing Approach

Reference [3] discusses a number of advantages of the distributed wireless network. Principal among these are the energy advantage and improvements in signal-to-noise ratio (SNR).

The energy advantage is a result of the strength of wireless signals being related to the square of the distance between transmitter and receiver. In a network of wireless transmitters where remote sensors communicate back to the central system by hopping their signals across the network the total transmitted distance is the same but each small hop requires less total power.

Although this advantage is useful for a large scale distributed network that may be proposed for an operational loads monitoring (OLM) program, the full advantage is not seen for one off monitoring of individual components, as a network of sensors would not be used.

The SNR improvement is a result of a larger number of sensors improving the chance that an available signal is above the noise floor of the sensor. Again, this is useful for a large scale distributed network that may be proposed for an OLM program, but is not relevant for one off monitoring of individual components.

The book focuses on three application examples to illustrate various aspects of wireless sensor networks. The first is habitat monitoring, where a number of sensors are used to determine meteorological data about an offshore bird nesting area. The second example is that of tracking a chemical plume. In this case the focus is on short lived sensors, sensing and transmitting geographical data (position, speed etc) of a hazardous chemical leak plume.

The final example is based on fixed sensors over a large area of a city communicating traffic flow information.

Due to the nature of each of these situations, the sensors are able to use quite low sampling rates, as the sensed data does not change quickly. The first two must rely on self contained power. The first example is able to rely on longer term power (solar or large capacity batteries), whilst the second has a weight limitation which will necessarily result in short lived sensors. The final example is able to be powered by standard area based power grids, as the sensor locations are geographically fixed.

In chapter 8 of [3] the authors identify some emerging applications. Briefly these are noted as;

- Asset and warehouse management.
- Automotive.
- Building monitoring and control.
- Environment monitoring.
- Health care.
- Industrial process control.
- Military battlefield awareness.
- Security and surveillance.

Without going into each area identified, each of these areas have aspects in common with OLM and one off load measuring of rotating components. Some of these areas also have similar security issues that will need to be identified and mitigated in the same way that transmission of data from operational defence platforms will have to be studied.

The most obvious item missing from each of the areas above is the difference in sensor rates required for the noted areas compared with the sorts of sample rates required for strain measuring.

Sampling of environmental qualities would expect to require sample rates much less than 1 sample per second. Although across the entire network many samples will be taken per second each sensor will only take a few samples a minute. In some cases, such as health care, military battlefield awareness and security and surveillance, even these smaller sample rates will only be transmitted when something is off interest.

These smaller sample rates allow the sensor to be put to sleep between samples and only be woken up for the sample and transmission if required. This will allow significant extension of battery lives.

In contrast strain rates on aircraft structure are typically completely at around 100 samples per second. The microprocessors (working at many MHz) can still be put to sleep between samples but much more thought will need to be put into efficient power consumption.

4.2 Wireless Sensor Networks

Wireless Sensor Networks addresses the design, analysis and deployment of wireless sensor networks. Of particular interest to this technical note is the security of data and energy efficiency concerns.

The book is organised into six parts:
- Basic concepts and energy efficiency,
- A discussion of various protocols for sensor networks,
- Data storage and manipulation in sensor networks,
- A discussion of security mechanisms,
- Network management techniques, and
- Target detection and habitat monitoring applications of sensor networks.

4.2.1 Data Security

Reference [4] discusses security in terms of planned malicious attacks on networks, either to gather private or classified information, or to bring down networks with some form of Denial-Of-Service (DOS) attack.

In terms of strain monitoring of defence assets both of these issues may apply. However, the nature of the strain monitoring proposed is unlikely to contain useful information that can be interpreted out of context by a data miner.

A DOS attack is also an unlikely scenario as proposed by [4] as the result of a DOS attack would not cause any obvious harm to the ADF platform, and certainly would not be expected to impede its operational use. A more likely scenario is that unintended DOS attacks cause overload of the strain sensing system.

This style of 'attack' would occur if the sensor was continuously required to verify a spurious signal inadvertently emitted by some electro-magnetic interference (EMI) to the extent that it caused loss of data as the network of sensors became overloaded with verification requests.

Protection against this non-malicious DOS attack does need to be considered and indeed should be tested for as part of the standard suite of EMI checks completed prior to deployment of a system on-board a defence asset.

4.2.2 Energy Efficient Design

Notwithstanding some newer options becoming available in the form of energy harvesting, wireless sensors need a source of power. Typically this is in the form of chemical batteries of various capacities. In a network of perhaps less than 50 sensors it is feasible to have shorter lived batteries as battery replacement is possible. However once the sensor network becomes larger, battery replacement becomes a prohibitively expensive proposition.

For this reason sensors must be designed to maximise battery life. Typical lifetimes should be measured in months if not years. Table 1 shows the capacity, in milliamp hours, of various sizes of alkaline battery. Table 2 shows the percentage of alkaline capacity that various other chemical batteries offer.

Table 1. Some Alkaline Battery Sizes and Capacities.[7]

Battery Size	**Capacity (mAh)**
D	12000
C	6000
AA	2000
AAA	1000
N	650
9 Volt	500
6 Volt	11000

It should be noted that although Table 2 gives capacities for various other chemical battery types, not all battery sizes are available with each chemical type. In addition the capacity of batteries will vary with the quality of the chemicals used in manufacturing.

Table 2. Alkaline Battery Types and Relative Capacity. [7,8]

Battery Type	% Capacity of Alkaline
Nickel-Cadmium	30
Lead-Acid	35
Silver-Zinc	85
Nickel Metal Hydride.	95

Critical to the resulting time that a device can work is the total power usage, typically in milliWatts (mW). The microprocessors can use between 10 and 500 mW when in use, and less than 1 mW in a sleep mode. The radio transmitters' power consumption is dependant on the range of the transmission required. A range of 10s of metres would require power of approximately 20 mW. Finally the sensors themselves need to be powered and the magnitude of this component is very much dependant on the type of sensor but would be expected to be approximately 50 mW.

Assuming a fairly energy efficient design (referred to in [4] as a "Battery Aware Design") should allow the entire system to consume around 100 mW peak and less if the processor is put into sleep mode and continuous transmission is not attempted. For a 3 volt system this corresponds to a current usage of 33 mA. This will mean that a 2000 mAh, AA size alkaline battery will run continuously for 60 hours. Of course two AA size batteries will be required for the 3 volts but the total capacity of the system wont change as the batteries will be in series.

4.3 Handbook of Sensor Networks: Compact Wireless and Wired Sensing Systems

Reference [5] is a recently published (2005) handbook covering both wireless and wired sensor systems. It covers a broad range of information in forty chapters by more than 90 authors. The chapters are divided into 8 sections focussing on:

- Applications,
- Architecture,
- Protocols,
- Tracking technologies,
- Data gathering and processing,
- Energy management,
- Security, reliability, and fault tolerance, and
- Performance and design aspects.

While not all of these are directly applicable to the particular subject of this technical note, the general field of wireless technologies is well served by these sections.

Although a lot of focus in this emerging area of technology has been on wireless capabilities, the reference discusses some very good reasons why wired sensor systems are still competitive. Principal amongst these reasons are data security and management of onboard

power sources. Both of these issues are fundamental to the use of these technologies in a military setting.

Some of the applications noted by [5] are in the fields of agriculture and environmental monitoring, civil engineering, health monitoring and surgery, and military applications. Here health monitoring is meant in the medical sense, but it could equally apply to the field of engineering health monitoring.

Some of the technical challenges noted are in the design of energy efficient nodes, cheap, reliable, high capacity power supplies, fault tolerance and security of information exchange.

It is noted that a per-node cost of US$100-200 is still too high and other sources have noted that this needs to drop by at least an order of magnitude to allow large sensor networks to be practical.

Energy harvesting is considered a practical solution to sensor power requirements. Chief amongst these are solar power. Exterior sunlight provides approximately 1 mW/mm^2 whilst bright indoor lighting provides around 1 $\mu W/mm^2$. The area term refers to the area of the solar collector.

Vibration energy is also noted and power outputs of 10 $\mu W/g$ of converter mass are quoted [9,10,15].

Other exotic power supply methods noted are the use of radioisotopes, excess heat from micro-rocket combustion, copper/zinc electrodes in sea water, and harvesting of Adenosine Triphosphate (ATP) for applications within living organisms.

In Chapter 32, reference [5] gives a very detailed discussion of denial of service (DOS) attacks that were mention above from reference [4]. This reference describes the type of attacker and their motivation, resources and intelligence/ability. These are noted as:

- Passerby – motivated by spontaneity, not determined, very little knowledge, few resources.
- Vandal – desire to inflict damage, perhaps visibility, moderately determined, little knowledge, few resources (often few resources are required as damage is the end goal).
- Hacker – desires access, motivated by curiosity and interest, highly determined, highly knowledgeable, moderate resources.
- Raider – driven by personal or organisational monetary or political gain, highly determined, moderately to highly knowledgeable, moderate resources.
- Terrorist or foreign power – desires real world damage by compromising vital system, very determined, highly knowledgeable, well resourced with time, money and manpower.

Interestingly, there is one additional type of attacker not mentioned here. This type of attacker differs from the list above in that it is not malicious. In fact the attacker may be completely unaware they are attacking the system. Any spurious radio signals may cause a network to

confirm the data. While it is unlikely that random transmissions will corrupt the data they may be strong enough to cause Jamming, Collisions, Exhaustion or Flooding as defined below.

A number of methods used by the types of attackers noted above are also listed. Most of the names are self-evident and outside the scope of this report to define in any great detail. They are:

- Jamming – deliberate interference to deny use of a communication channel.
- Tampering – Damage caused by physical access to an individual node.
- Collisions – Similar to jamming, but rather than stopping the transmission the attacker seeks to transmit at the same time. This causes packets of information to collide and become unreadable.
- Exhaustion and interrogation – caused by repeated requests for retransmission, causing battery exhaustion.
- Selective forwarding – A particular node is subverted by an attacker. The node then advertises itself as a "desirable path" but simultaneously does not transmit any information received. This node then becomes a "black hole" for information packets.
- Misdirection – in a large network of sensors, a subverted node is used to send information to other nodes and advertise this new path as "desirable". This acts to slow the network and ultimately cause the network to fail as information enters endless loops or the power source is exhausted.
- Sinkholes – attack is similar to a black hole but the intent is to eavesdrop on the data rather than block its transmission. Ideally the network owner is unaware of the sinkhole.
- Sybil attack – as the name suggests, this attack consists of a single node impersonating several nodes to increase the chance of information being routed through that node.
- Flooding – this attack overwhelms a node by causing other nodes to communicate with it. This is achieved by faked the victim node and requesting information from multiple nodes in a network. All these nodes then attempt to communicate with the victim. A variation of this attack is the HELLO flood, where an attacker advertises its presence in a network to every node. A handshake routine ensues, which blocks information exchange.
- Algorithmic complexity attack – this attack is used when a highly complex algorithm is used to confirm traffic signals. It is this very complexity that allows an attacker to send data that takes a long time to process. This will result in lower system performance and power exhaustion.

There is one additional type of attack not mentioned here: Data Corruption – this style of attack consists of taking the correct data and changing the data to give false information. As an example in the defence area, this may have the effect of causing an unnecessary maintenance action when data is changed to indicate a false positive for an oil particle sensor. Alternatively, strain values may be tampered with to indicate false highs (to cause an unnecessary maintenance action) or false lows (to cause an undetected failure to lead to loss of an aircraft).

The use of networks for measuring rotating components and operational load monitoring will require well thought out designs. The design will need to anticipate and incorporate a robust system capable of defending against all of the noted attacks regardless of the intent of the attacker.

4.4 Sensors, Nanoscience, Biomedical Engineering, and Instruments

Although [6] is quite a lengthy reference most of it deals with biomedical sensors and their applications. Some of this is relevant to sensing of operational loads and loads in rotating components but only in an indirect way.

The most relevant aspect of this reference is in the early part of the book dealing with multi-sensor data fusion. This is discussed with reference to condition based monitoring of complex systems using the particular example of the helicopter, although any complex machinery would serve. These systems consist of large arrays of sensors. Reference [6] specifically mentions MEMS (micro-electrical mechanical systems) but any array of accelerometers, strain gauges, humidity sensors etc could be included. These sensors are used to determine the status of machinery, evidence of impending failure classification of fault conditions and predictions of time to failure.

Condition based monitoring seeks to improve safety and maintenance costs by reducing unnecessary maintenance. Recalling the bathtub model of failure indicates that at least some failures are the result of maintenance, and of course maintenance itself is an expensive undertaking with around 40% of life cycle costs directly related to maintenance. These issues are expanded on in [11,12,13,14].

Although not relevant to the study of operational loads or loads in rotating components, reference [6] also has a discussion of the use of piezoelectric sensors to find cracks in structural components.

5. Some Commercial Solutions for Loads Monitoring

In this section a selection of available commercial applications is presented. This selection is by no means exhaustive and further research is easily achieved with a simple web based search of applicable key words. This section is meant as guide to the sort of work that has been practically successful in commercialising theoretical ideas in the field.

5.1 AVD Portable Strain Gauge with On-Board Data Storage

The Air Vehicles Division (AVD) of DSTO has a yearly task to develop innovative ideas proposed by its staff. In 2003 the author, Chris Knight, and Peter Smith developed the idea of a portable strain gauge with on-board data storage to replace the existing method of strain gauge data collection. At that time the existing data collection method consisted of strain gauges at the required location, linked via wires back to a central signal conditioning and data storage computer.

The device is a multi-channel strain gauge system with on-board signal conditioning. The output from each strain gauge is stored on non-volatile RAM disks (e.g. MMC, SD card) for post collection manipulation and analysis. The unit is battery powered for portability.

The system can interface with Secure Digital (SD) and MultiMedia Card (MMC) types, which are currently available with more than 2 GB capacity. This corresponds to approximately 20 days of non-stop measurement at the full data capture rate of 200 samples/sec/channel. The system can support up to 3 channels.

The block diagram below shows the basic setup. To the left are the three strain gauges connected back to the signal conditioning and amplifiers. The data is then written to MMC or SD storage cards via a USB style connection. The data storage module, on the right also supplies power to the entire device.

Features include:

- Compact and light weight,
- On-board signal conditioning,
- On-board data storage for "set-and-forget" operation,
- Battery powered for remote operation,
- Battery state indication,
- Number of strain gauges up to 3 is settable
- Temperature detection/compensation
- Power reset
- Memory overwrite protection
- Variable Sample Rate

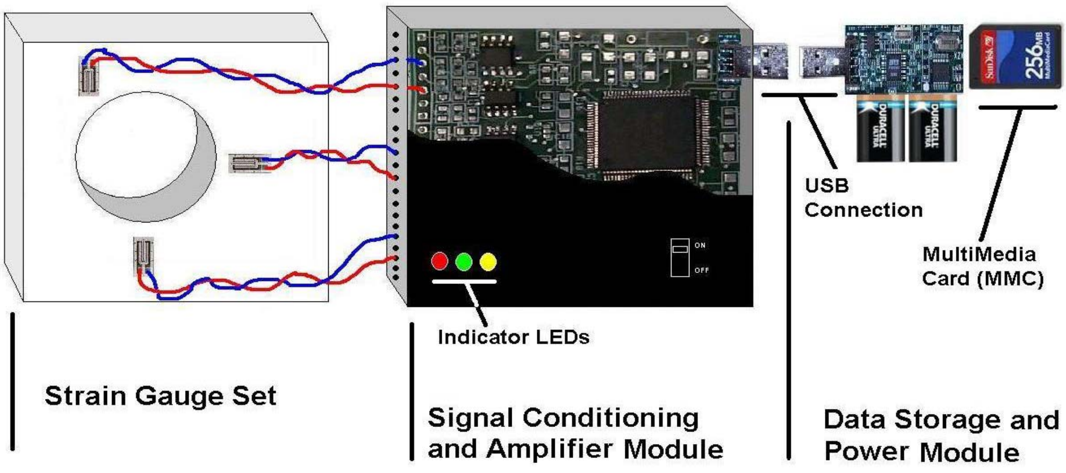

Figure 1. The Basic Layout of the AVD Strain Gauge

The advantage for this device for operational loads monitoring and load monitoring for rotational components resides in its ability to reliably log data over an extended period of time in a compact and low power system, without the use of exotic wireless devices that are

currently problematic within the defence environment. Availability of this system will allow more extensive strain gauging without incurring exorbitant hardware overhead costs.

Although there are currently wireless systems available, Defence operational limitations do not allow unauthorised transmissions (Blue Tooth, WiFi, etc) from defence resources. This device's on-board data storage for later retrieval offers a significant advantage over wireless devices.

This system has some disadvantages for operational loads monitoring. When the system was originally conceived it was intended for strain monitoring across three channels located in close proximity to one another (within a few meters). Operational loads monitoring usually requires many more channels and they need to be time synchronised both with each other and with flight parameters like aircraft speed, altitude and angle-of-bank.

In addition, if there are many disks that need to be collected, both the collection and synchronisation of the data will become an onerous task.

Table 3. Key specifications for the AVD Strain Gauge

Strain Range	0 to ±3000 με
Strain Resolution	3 με
Strain Accuracy	30 με (1% at Full Scale)
Strain Bandwidth	DC – 200 Hz
Number of Channels	3 (full bridge)
Gauge Impedance	120, 350 and 1000 Ω
Gauge Excitation	3V
Signal Conditioning	• 40 Gain, 2 stage Amplifier • 12 bit A-D Conversion (on board micro-controller)
Maximum Voltage Supply	16 V (requires 3V)
Power Source	On board alkaline battery, AA size x 2
Power consumption	60 - 255 mW @ 3V (dependant on gauge resistance)
Recording time	(13 to 55 hours from standard AA batteries)
Sample Rate	Up to 200 samples/sec
Word Size	16 bit system
Storage Capacity	Cards available exceed 2 GB
Storage Medium	Removable SD or MMC Flash Memory
Transducer Types	Any transducer that provides an output in the10–500 mV range (temperature, pressure, accelerometer etc)
Size (excl. transducer leads)	50mmx50mmx15

5.1.1 Military Applications

- Mechanical testing of military vehicles and structures, especially all types of aircraft, fixed wing and rotary wing.
- Load sensing on rotating component where noisy slip rings would otherwise be needed:
  - Helicopter main/tail rotor and pitch control rods
  - Drive and crank shafts
  - Ship propellers
- Load sensing on size/weight critical applications such as Unmanned Air Vehicles (UAVs)
  - Wing loads
  - "Black Box" flight recorder
- Load sensing inside enclosed vessels where no wire penetration is allowed:
  - Fuel tanks
  - Pressure vessels
  - Wing boxes
  - Hollow structural sections

5.1.2 Commercial Applications

- The Portable Strain Gauge systems would find applications in the commercial equivalents of the above. In addition:
- Remote sensing/logging of:
  - Rail and road bridge loads
  - Rail track loads
  - Building loads

The system is currently at the advanced prototype stage. Components have been integrated with each other but live strain gauge feeds have not been collected. Unfortunately, due to a reduction in staffing within the infrastructure group of the Air Vehicles Division, no further developmental work is envisaged.

5.2 MicroStrain Inc.

MicroStrain (http://www.microstrain.com) is a privately held corporation in Williston, Vermont. It has operated since 1987 and manufactures a wide range of miniature sensors for various biomedical, military and other engineering applications.

MicroStrain manufactures a range of displacement transducers, orientation sensors, force probes and wireless sensors. They also manufacture a range of data loggers and signal conditioners suited for their product range.

The wireless sensors come in five basic families:

- Agile Link wireless sensor and data acquisition system.
- 2400 series wireless nodes.

- 2400 LDC low duty cycle nodes.
- 900/868 series wireless nodes.
- Embedded series.

Figure 2. EmbedSense Wireless Sensor (www.microstrain.com)

The Agile Link wireless sensor (Figure 3.) is about the size of a postage stamp and can convert multiple sensor streams into a single data stream which is then transmitted back to a base station for storage and manipulation.

The 2400, 2400 LDC and 900/868 series nodes are families of analogue input data loggers and transmitters. The 2400 and 900/868 series have voltage, strain gauge and accelerometer inputs at higher sample rates whilst the 2400 LDC series is at a lower sample rate to suite thermocouple inputs. The 900/868 series accept 8 channels of input whilst the 2400 appears to have two channels. It is not clear what the actual sample rates are but it appears to be up to a maximum of 2048 samples / sec. This may equate to 256 samples / second / channel.

The embedded series, shown in Figure 3., are self contained units that are read in situ by a remote reader that also supplies power. The website does not indicate if the device has onboard storage or whether the sampling is done only when the reader is providing power. The latter is more likely, unless the sample rate is so low that onboard storage is feasible.

Other work by MicroStrain in the area of strain energy harvesting (http://www.microstrain.com/white-strain-energy-harvesting.aspx) has the potential to eliminate batteries for longer term, wireless monitoring of structures. In the MicroStrain system, strain energy from the motion of the component being investigated, is stored by rectifying output from piezoelectric fibres, into a capacitor bank. When the capacitor voltage reached a predetermined threshold, its charge is transferred to an associated wireless sensor node.

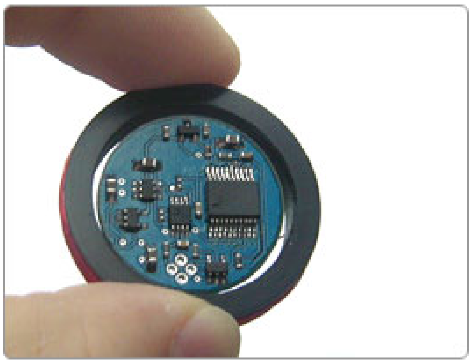

Figure 3. EmbedSense Wireless Sensor (www.microstrain.com)

Similar work by DSTO, RMIT and Victoria University [15], once again using piezoelectric devices and novel circuit approaches, shows that power harvesting from vibratory structural members is sufficient to drive power efficient circuitry. The power in both these cases is provided by structural damping of the member being investigated.

5.3 Millennial Net

Millennial Net (http://www.millennialnet.com) is a privately owned, venture backed company based in Burlington, Massachusetts in the United States. They develop wireless sensor network software and hardware for original equipment manufacturers.

The focus of Millennial Net offerings is a system known as MeshScape. The MeshScape system was designed specifically for commercial and industrial wireless sensor networking applications. Although the hardware put together for the MeshScape system is powerful, Millennial Net has also invested considerable effort in a wireless protocol that is scalable, energy efficient, responsive and reliable.

Often in large networks that are dynamic (the nodes move relative to one another) a substantial amount of computing time, and thus power consumption is spent determining the most efficient path for data signals to take. These are called "discovery packets" and there sole purpose is to determine a path back to the storage medium. The more discovery packets that are sent, the less real data can be sent, and the more power required for the system of nodes.

The key difference is that in other wireless networks the discovery packets are sent globally, whilst in the Millennial Net system this performed locally. This results in a process of "self healing", across the network.

Strictly speaking this should not be required for either operational loads monitoring or for remote load sensing of rotating components. The reason for this is that in both of these situations the topology of the networks (the relative positions of nodes) should not change with time. However, if data is transmitted between nodes before reaching the central data store then it may be wise to invoke this sort of 'self healing' to reduce the impact of node failure and improve the system robustness.

Millennial Net declares a battery life of 10+ years. This is quite remarkable. In fact most batteries have shelf lives much shorter than this and the various types of rechargeable batteries have quite poor self-discharge lives.

These sorts of battery lives may be achievable with very low sensor rates, and indeed a lot of the companies work has to do with Heating Ventilation and Air Conditioning (HVAC) systems. Typically sensor rates for temperatures and humilities are approximately one sample per minute. The requirement for strain gauge and accelerometer measurements is often higher than 6000 samples per minute. At these rates battery lives are very short, of the order of hours, and some form of energy harvesting is required for practical measurements.

5.4 EnOcean (www.enocean.com)

EnOcean is a German company founded in 2001 as a spin-off from the Siemens company. The company specialises in wireless sensor networks with two key differences from most wireless networks. The first difference is a set of innovative methods of off-board energy harvesting. The second couples this technology with extremely low power requirement sensors and radio transmission devices.

At this stage the system does not seem to have quite enough power for applications at the high sensor rates required for operational load monitoring or measurement of loads in rotating components. However, with some advances in technology, energy harvesting may be able to supply the required energy densities for high rate sensor applications.

EnOcean's energy harvesting technology is focussed in three areas; mechanical, thermal and light energy. Mechanical energy harvesting is based on piezoelectric devices that give off electrical energy when strained. Thermal harvesting is based on thermocouples and light harvesting is based on solar panels.

Table 4. A review of EnOcean's energy harvesting processes. Based on [16], Figure 1.

Energy Source	**Mechanical**	**Thermal**	**Light**
Conversion Device	Piezoelectric	Thermocouples	Photovoltaic Cell
Dimensions[4] (mm)	20 x 6 x 1	5 x 5 x 2 mm	10 x 20 x 2 mm
Production Costs ($A)[5]	3	5	1.60
Source of Energy	e.g. Button push, 3 mm @ 5 N	Temperature Difference of 5 K	Light, 400 lux[6]
Energy/Power Output	200 µWs per operation	20 µW permanently	20 µW permanently

EnOceans devices currently consist of remote control type devices where the energy harvested is used to transmit commands such as on or off to a controller for a light or a window blind.

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[4] This refers to the dimension of the element used for generating the energy.
[5] Based on an exchange rate of €0.6 / $A and a production run exceeding 10,000 units.
[6] A normal office space is approximately 500 lux and an operating theatre is approximately 1000 lux (from www.engineeringtoolbox.com).

6. Commercial Contact Activity

One of the aims of this report was to gather information for and example system for both Operational Loads Monitoring and Rotating Component load monitoring. The system example was proposed to include basic system architecture, system limitations and rough order of magnitude (ROM) costs.

MicroStrain were initially contacted and although their system was indicated as not flight ready, DSTO was prepared to accept that this system could be made flight ready with a suitable injection of funds.

The proposed system was for both the fixed wing and helicopter system as they are not considered significantly different for a ROM analysis. This system was outlined to MicroStrain as follows;

- Approximately 80 strain gauges (120 or 350 Ohm).
- Approximately 20 Accelerometers
- Approximately 20 cockpit gauge repeaters (to enable flight control position monitoring)
- Sample rates for strain gauges to exceed 100 samples / second and accelerometers and gauge repeaters to exceed 20 samples / second.
- The system will be installed for approximately 6 months.
- The system should include all components required for this, including;
    - Data acquisition
    - Amplifiers
    - Signal Conditioning
    - Data storage

The response from MicroStrain indicated that the system was not able to meet these requirements and a significant development cost would be required.

A follow-up email of similar content was sent to CrossBow which offers a similar system capability to MicroStrain. The response was similar.

MicroStrain and Crossbow were contacted regarding large scale, multi channel installations in aircraft trials. Although neither company could provide a solution for this particular style of installation, both companies are capable of producing a wireless transducer solution on a smaller scale (less than 10-20 gauges), for ground based trials. The issue preventing larger scale solutions on aircraft trials is one of channel crosstalk, expense of transmitters and the current power use of these systems, which limits the time between maintenance. A secondary issue is the difficulty in certifying these systems in flying aircraft where interaction with safety-of-flight hardware and software onboard the aircraft cannot be determined without a much larger effort.

7. Future Predictions

It is difficult to make any firm predictions in such a fast moving field as sensors and electronics. However, a generally safe prediction is that electronics will get smaller, faster, more efficient and cheaper. With these four general predictions some broader claims can be justified.

It seems a reasonable prediction that more and more wireless sensors and wireless sensor networks will be found in the broader scientific community. Whether the defence community adopts these technologies at the same rate will depend very much on the willingness to rethink existing policy such as the limitation on wireless products within defence.

The ability of devices to self-power is still in its infancy, but more of this sort of technology will be found simply because batteries are expensive and require regular replacement. As the sensor electronics get more efficient, the requirement for large energy storage systems like batteries will decrease and more of these devices will be powered by the motions of the component being studied. Alternative sources of power, like ambient light or heat, when combined with efficient sensor networks will allow discarding of relatively bulky batteries.

Embedded technology, outside the laboratory, should be expected to begin soon as the existing wireless technologies prove their reliability and more manufacturers are willing to take a technological risk. If the perceived risk of using these technologies allows a benefit that can be sold at a premium, then manufacturers will surely adopt some of these technologies.

One shortcoming of the current crop of wireless technologies, particularly when these technologies are used in a sensor network, is the simplistic nature of their self-test procedures. Currently these tests are capable of detecting if a sensor has failed completely but are unable to sense a need for recalibration. With the advent of self-diagnosis and self-repair, sensors should be able to work almost indefinitely.

Finally, as each of these components combine, we should see more applications where entire structures, bridges, aircraft or ships are networked to enable usage monitoring and health reporting. This will drive a change from the current methodology of preventative maintenance to a process of on-condition maintenance for entire platforms. This sort of network is envisaged for the Joint Strike Fighter and will only become more widespread when the advantages of the system, and its short comings are recognised.

8. Conclusions

Existing methods of load monitoring are known to be expensive and particularly expensive to install. The area of wireless monitoring has been shown to be maturing quickly. However, the existing wireless sensor network systems offer insufficient capabilities for either operational loads monitoring or monitoring of rotating components.

The major shortfalls for the technology are in sensor rates and the requirement to replace batteries frequently. There is also a minor issue of communications bandwidth in large sensor networks.

The issue of sensor rates is particularly relevant to loads monitoring of rotating components. Currently the low sensor rates do not allow for practical use of these sensors for measuring vibratory loads.

The question of battery use has been shown to be particularly relevant to operational loads monitoring where the sensors are mounted on the platform for long periods of time to assess the usage and loads of that platform.

The available sensor rates should increase in line with Moore's Law[7] and thus DSTO resources would be poorly applied to the problem of increasing sensor rates. However the issue of reliance on battery power has shown some interesting solutions in the form of power harvesting.

The existing defence policy on wireless communication will limit the ability to use these devices, both operationally and for test and trials. However, sensible application supported by relevant changes to the policy should allow this hurdle to pass easily.

[7] A statement by Intel co-founder, Gordon Moore, regarding the pace of semiconductor technology. In general it states that the speed or capabilities of a computer based system doubles approximately every 18 months.

9. Recommendations

It is recommended that, in the mid to long term DSTO should give more thought to applying wireless sensor networks to platform loads monitoring. However, this work should be solidly based on in-house development in leading technology areas such as power harvesting, coupled with external growth in sensor rates and solutions to communication issues.

Some existing work within DSTO [15] has already been applied to the issue of power harvesting, and DSTO resources should grow within this area. This area is still immature technology and ample opportunity exists to commercialise any results through the DSTO Business Office.

It is also recommended that DSTO provide input, and possibly consider forming a working group to assess the existing policy of wireless networks within defence. The focus of DSTO input should be in endeavouring to provide secure access for wireless communication. This should be initially on flight test platforms in non-operational areas, however, the feasibility of an extension to operational platforms should be considered.

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19. ABSTRACT

A variety of new wireless technologies offer some advantages when used for direct strain monitoring of rotating components, particularly for rotary wing aircraft. This technical note investigates some of these technologies, including one developed in house by Air Vehicles Division. The use of wireless technology is advantageous as it avoids the use of slip rings and other current methods for monitoring strain where the component to be investigated rotates relative to the rest of the vehicle. Investigation of these same technologies for use when retrofitted to fixed wing aircraft or in non-rotating components is also presented. In this situation the advantage offered by these devices is the simplicity, convenience and speed with which they can be applied to usage and loads assessment. It is concluded that DSTO should adopt wireless sensors for an array of load monitoring uses and actively research in leading areas such as power harvesting.